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Closing maize yield gaps in sub-Saharan Africa will boost soil N_2O emissions

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In sub-Saharan Africa (SSA), the most important staple crop is maize; the production of which is dominated by smallholder farming systems using low external inputs (<10 kg N ha^{-1}) resulting in low crop yields and large yield gaps (difference between actual and potential yields). To assess increases in soil N_2O emissions when closing maize yield gaps by increased fertilizer use, we reviewed the literature, developed a relationship between yield gaps and soil N_2O emissions, and used it to scale across SSA. According to our analysis, N_2O emissions from maize production will increase from currently 255 to 1755 ± 226 Gg N_2O-N year^{-1} (+589%) if existing maize yield gaps are closed by 75%, increasing total anthropogenic N_2O emissions for SSA by c. 50%.

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Introduction

Food insecurity is a major challenge worldwide, with approximately 820 million people affected [1]. This problem is exacerbated in sub-Saharan Africa (SSA) where c. 25% of households are considered permanently food insecure, with that number rising to c. 40% of households during certain 'lean' times of the year such as during the dry season [2]. As the world population is expected to increase from eight to ten billion in the next 40 years, with about half of that increase occurring in SSA [3], the issue of food insecurity will likely worsen unless more food can be produced locally or imported from elsewhere.

Smallholder agriculture (here farms <2 ha) is the dominant form of agricultural crop production in SSA, contributing the majority of food production at the national level [4]. This type of agricultural production is characterized by low inputs, with mean annual synthetic N fertilizer use in SSA ranging from 7 kg N ha^{-1} in West Africa to 13 kg N ha^{-1} in East Africa [5•,6,7]. In many regions of SSA, organic fertilizers such as manure or plant residues, including intercropping with legumes, are used on croplands; however, few data are available regarding application rates and N content of these organic fertilizers [8], which can vary substantially even at farm scale [9•] with manure management and type of plant residue. Such low N inputs lead to depletion of soil N stocks characterized as soil 'N mining' [10,11], one of the main reasons for soil fertility losses and low crop yields. Annual yields for maize (*Zea mays*), the primary staple food crop in SSA, from 2015 to 2018 in SSA averaged a little over 2 Mg ha^{-1} [12], that is, approximately 20% of the average maize yields in North America or Europe. While a direct comparison might not be suitable as yields depend not only on crop management but also on soil and climatic conditions, it remains indisputable that current yields in SSA are much lower than what could potentially be produced, creating what is known as a 'yield gap' (i.e., the difference between the potential yield — if plant growth is not limited by nutrient or water deficiencies — and the actual yield).

Currently, agricultural production in SSA is increased primarily by expansion of agricultural land [13], causing forest degradation and deforestation [14•,15] and conversion of native savannah grassland to agricultural land [16]. These land use changes are associated with loss of biomass and soil organic carbon (SOC), leading to enhanced greenhouse gas (GHG) emissions [17•]. Furthermore, land suitable for agricultural production is already limited in many SSA countries with some existing agricultural lands already becoming unproductive due to soil degradation and climate change. As a result, cropland expansion can also lead to displacement, conflicts [18] and loss of biodiversity [19,20]. To reduce the pressure on natural land, sustainable intensification of agricultural production on existing cropland [21,22] is required. However, it remains unknown how this intensification will affect nitrous oxide (N_2O) emissions from cropland soils, with N_2O being a potent GHG with 265-times the global warming potential of carbon dioxide (CO_2) per mass over a 100-year time horizon [23], and the most dominant ozone-depleting agent of the 21st century [24].

Will closing yield gaps increase soil N_2O emissions?

Increasing agricultural production in SSA without land expansion requires increased fertilizer inputs [25] as well as improved water management. Increasing fertilizer application rates beyond a certain threshold (between 100–150 kg N ha^{-1} [26••,27]) has been shown to cause a non-linear increase in direct N_2O emissions (i.e., N_2O that is emitted on-site from soils to which N is added) [26••]. In addition, fertilization promotes indirect N_2O emissions, which arise (i) from volatilization of ammonia (NH_3) and nitric oxides (NO_x) from fertilized soils and re-deposition elsewhere, as well as (ii) from runoff and leaching of N from fertilized soils, with N_2O being produced along these hydrological and gaseous loss pathways. This study focuses on direct N_2O emissions from cropland soils.

Exponential increases in N_2O emissions occur at N fertilization rates greater than crop N demand [26••,28••]. This is currently not a concern in SSA as current fertilization rates are low (ranging from 7 to 13 kg N ha^{-1} [6]), and previous studies in western Kenya have shown that increased N_2O emissions only occur if seasonal N application rates are >100 kg N ha^{-1} [27,29]. Yields of most crops, but in particular maize, are limited not only by N limitation but also by water availability as water deficits in SSA are often present at critical times during crop development [30]. Very few smallholder farmers in SSA irrigate their crops because the potential benefits tend to be low compared with the costs [31], and/or because water is scarce; a condition that, with the exception of east Africa, will be exacerbated by climate change [32]. Better water management though, can also be accomplished by soil and water conservation approaches such as terracing [33,34], water harvesting [35] or by increasing soil organic matter (SOM) and thus improving soil water holding capacity (WHC) through conservation agriculture practices of reduced tillage and residue retention [36]. Increased SOM content, water conservation, and irrigation will likely create more anaerobic microsites that, in conjunction with the application of N fertilizers, can result in greater denitrification rates that will likely lead to enhanced N_2O fluxes [37–39].

Reduction of food insecurity, sustainable intensification of agricultural systems, and mitigation of climate change are major 'challenges of our time' [40]. With the present study, we are providing some critical information to assist policy makers in balancing them appropriately.

Yield-scaled N_2O emissions

Increasing N_2O emissions per unit of area may still be an acceptable strategy if the amount of N_2O emitted per unit of food product, also known as yield-scaled emissions [28••], does not increase, and if it prevents conversion of existing natural areas to agricultural lands. In SSA, even though N_2O emissions per unit of area tend to be small when N inputs are less than 50 kg N ha^{-1} [41], yield-scaled emissions are often higher than those observed for intensively managed croplands outside of SSA due to the extremely low crop yields [42,43]. This suggests that increasing N fertilization to reduce the yield gap in SSA agriculture may have only minor effects on yield-scaled N_2O emissions, even if total N_2O emissions from croplands increase.

However, it remains unclear how much these yield gaps can be closed through additional N application before total and yield-scaled N_2O emissions begin to rapidly rise. Therefore, the objective of this study is to summarize the current knowledge on the link between maize yield gaps and soil N_2O fluxes and to use that summary data to determine how improving crop yields (i.e., reducing the yield gap) by increased fertilizer application may impact total area and yield-scaled N_2O emissions in SSA.

Establishing a link between yield gaps and soil N_2O emissions

Data on N_2O emissions were collected from the peer-reviewed literature by searching Scopus, Google Scholar and Web of Science using the key words 'Africa', 'agriculture' and either 'nitrous oxide' or 'N_2O' (until and including year 2019). We also used the database of African GHG studies from Kim *et al.* [41] to identify additional publications. This yielded a total of 71 peer-reviewed publications. Of those, only studies that had measured both crop yields and soil N_2O emissions in the field for at least one full cropping season were included (14 publications). Of these publications, eight studies had been conducted in maize fields (Table 1), while the other studies had measured rape (n = 2), vegetables (n = 2), millet (n = 1) or sorghum (n = 1). Therefore, we limited our focus to maize production systems. In addition, we included unpublished data from our own measurements in Kenya (Rogers Rogito and Peter Mosongo, personal communication). A single study tested the effect of irrigation on maize yields and soil N_2O emissions (Peter Mosongo, personal communication). To improve the strength of the dataset, we added studies that measured

Table 1

List of peer-reviewed publications and MSc theses measuring soil N_2O emissions and maize yields in tropical and subtropical regions worldwide that were used as data source for the present study

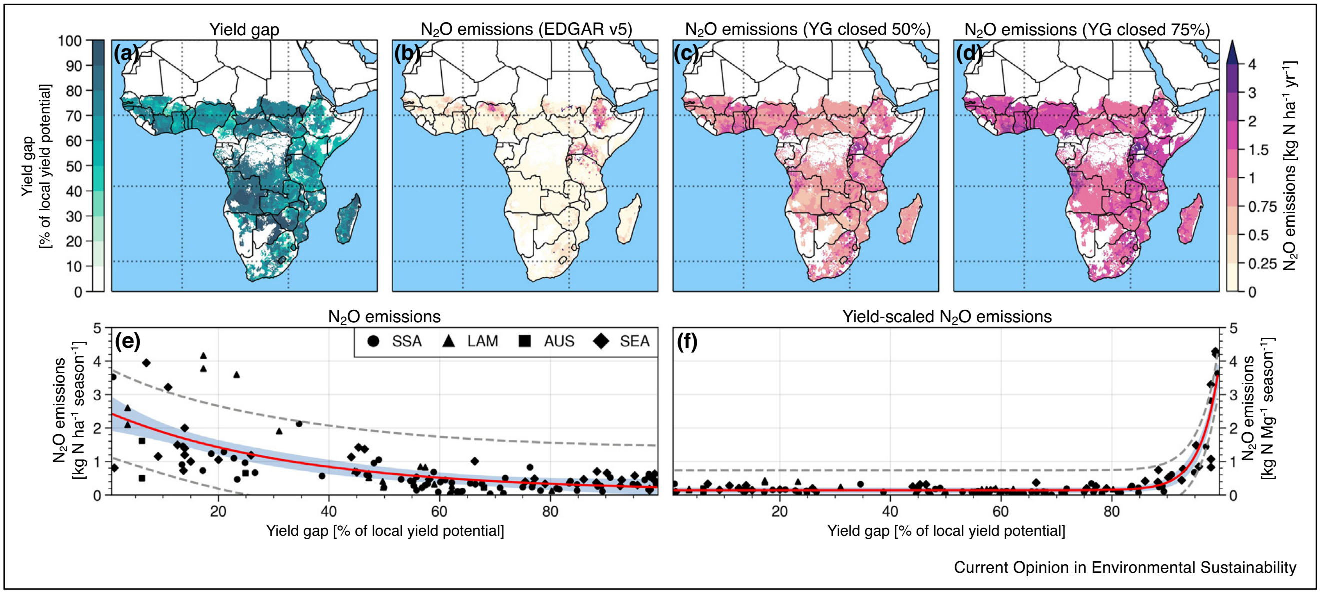
Publication	Country	Location	Management	Soil type	Soil texture		Soil organic C (g kg DM^{-1})	Fertilization rate[a] (kg N ha^{-1})	N_2O flux (µg N m^{-2} h^{-1})	Cumulative N_2O emissions (kg N ha^{-1})	Yield-scaled N_2O emissions (kg N Mg^{-1})	Grain yields (Mg $seas^{-1}$)
					Sand (%)	Clay (%)						
Sub-Sahara Africa												
Chikowo *et al.* [50]	Zimbabwe	Domboshawa	Improved fallow and legume residue incorporation	Lixisol	73	22	6.0	0–109	4.2–51.3	0.10–0.50	0.11–0.22	1.0–2.6
Hickman *et al.* [27]	Kenya	Yala (Siaya)	Synthetic fertilizer	Oxisol	52	35	19.0	50–200	2.1–100.0	0.04–0.33	0.01–0.08	2.9–4.6
Hickman *et al.* [29]	Kenya	Maseno	Synthetic fertilizer	Nitisol	26	53	20.9	50–200	2.3–259	0.41–0.54	0.09–0.12	4.0–4.8
Kimetu *et al.* [51]	Kenya	Kabete	Synthetic and organic fertilizer	Humic Nitisol	23	40	16.0	0–60	−0.3–12.3	0.04–0.37	0.01–0.10	3.0–3.9
Nyamadzawo *et al.* [52]	Zimbabwe	Domboshawa	Synthetic and organic fertilizer, ISFM[b]	Haplic Lixisol	83	4	6.0	0–120	90.3–180.6	0.26–0.53	0.23–0.68	0.5–1.6
Pelster *et al.* [42]	Kenya	Nyando	Synthetic and organic fertilizer	Nitisol	–	–	–	0–25	−74.7–390.3	0.05–0.98	0.06–0.43	0.1–0.8
Sommer *et al.* [53]	Kenya	Madeya (Kisumu)	Synthetic and organic fertilizer, ISFM[b]	Acric Ferralsol	–	55	17.0	0–176	5.1–190.2	0.24–0.35	0.09–0.35	2.5–3.5
Kimaro *et al.* [43]	Tanzania	Kolero, Uluguru Mts	Synthetic and organic fertilizer, legume intercrop., conservation agriculture	Ferralsol	67	21	27.0	0–100	4.6–11.4	0.13–0.23	0.05–0.09	1.9–2.8
Macharia *et al.* [54]	Kenya	Machang'a (Embu)	Synthetic and organic fertilizer	Xanthic Ferralsol	67	22	9.9	0–60	3.91–57.0	0.33–0.83	0.34–3.63	0.1–2.4
Peter Mosongo (personal communication)	Kenya	Kiambu	Synthetic and organic fertilizer, legume intercrop., irrigation	Chromic Vertisol	12	62	29.8	0–140	5.0–190.2	0.69–1.46	0.13–0.18	4.2–8.8
Rogers Rogito (2019), MSc thesis [77]	Kenya	Aludeka (Busia)	Synthetic and organic fertilizer	Orthic Acrisol	31	14	5.6	0–241	19.7–324.0	0.32–3.53	0.04–0.27	2.4–10.6
		Sidada (Siaya)	Synthetic and organic fertilizer	Dystric Nitisol	11	56	20.9	0–237	−26.4–637.4	0.22–1.10	0.02–0.36	5.1–9.2
Latin America												
Aita *et al.* [55]	Brazil	Rio Grande do Sul	Synthetic and organic fertilizer, irrigation	Haplic Acrisol (Alumic, Rhodic)	44	19	20.5	0–168	0–2302.0	1.91–4.16	0.24–0.43	8.1–9.7

Table 1 (*Continued*)

Publication	Country	Location	Management	Soil type	Soil texture		Soil organic C (g kg DM^{-1})	Fertilization rate[a] (kg N ha^{-1})	N_2O flux (μg N m^{-2} h^{-1})	Cumulative N_2O emissions (kg N ha^{-1})	Yield-scaled N_2O emissions (kg N Mg^{-1})	Grain yields (Mg seas^{-1})
					Sand (%)	Clay (%)						
Bayer *et al*. [56]	Brazil	Rio Grande do Sul	Organic fertilizer (residue), irrigation	Alumic Acrisol	54	22	–	0–115	−24–104	0.13–0.27	0.11–0.18	2.3–4.4
Jantalia *et al*. [57]	Brazil	Rio Grande do Sul	Organic fertilizer (residue)	Rhodic Ferrasol	24	63	16.0	0–87	8.1–150.0	0.22–0.33	0.11–0.20	4.8–5.9
Martins *et al*. [58]	Brazil	Bahia	Synthetic fertilizer	Oxisol	74	21	6.4	0–160	0–190.9	0.41–0.72	0.07–0.11	5.9–6.2
Grageda-Cabrera *et al*. [59]	Mexico	Celaya	Synthetic fertilizer, irrigation	Typic Pellustert	–	–	11.2	0–240	13.5–1298.7	2.10–2.60	0.15–0.18	10.5–14.6
Petitjean *et al*. [60]	French Guyana	Sinnamary	Synthetic fertilizer	Hyper-ferralic Ferralsol	72	25	–	169	−1.9–65.8	0.78–0.85	0.17	5.1
SE Asia												
Zhai *et al*. [61]	China	Hunan	Synthetic and organic fertilizer, irrigation	Ferralic Cambisol	–	–	6.1	0–210	0–110.0	0.14–1.42	0.32–1.07	0.2–4.4
Afreh *et al*. [62]	China	Jiangxi	Synthetic and organic fertilizer	–	–	–	9.4	0–60	10.4–47.6	0.30–1.37	0.09–4.29	0.1–9.3
Xie *et al*. [63]	China	Hunan	Synthetic fertilizer	–	–	–	14.6	0–240	60.0–150.0	0.40–2.00	0.14–0.29	2.0–7.1
Veldkamp *et al*. [64]	Indonesia	Palu	No fertilizer	–	–	–	22.0	0	29.2–120.8	0.66	0.52	0.5
Weller *et al*. [65]	Philippines	Los Banos	Synthetic fertilizer, irrigation	Anda-queptic Haplaquoll	13	54	18.0	0–190	21.9–137.2	0.63–3.95	0.28–4.2	0.3–4.2
Australia												
Migliorati *et al*. [66]	Australia	Taabinga, Queensland	Synthetic fertilizer, irrigation	Ferralsol	31	55	14.7	40–160	2.5–305.0	0.22–1.61	0.06–0.19	2.6–8.5

[a] Range of fertilization rate per cropping season.
[b] ISFM, Integrated Soil Fertility Management.

Figure 1



(a) Current seasonal maize yield gaps (% of local yield potential) for sub-Saharan Africa (SSA) based on data from Mueller *et al*. [5•]; **(b)** current cumulative N_2O emissions from EDGAR v5.0 [49]; **(c)** and **(d)** cumulative N_2O emissions when maize yield gaps are closed by 50% or 75%; **(e)** relationship between maize yield gaps (% of local water-limited yield potential, Y_w) and cumulative soil N_2O emissions (kg N_2O-N ha^{-1} season^{-1}) that was used to calculate the maps in panels (c) and (d); **(f)**, relationship between maize yield gaps (% Y_w) and yield-scaled soil N_2O emissions (kg N_2O-N Mg^{-1} yield). Data for panels (e) and (f) are derived from field studies with maize in SSA, Latin America (LAM), Australia (AUS) and south-east Asia (SEA) (Table 1). The blue area in panels (e) and (f) represents the 95% confidence interval, the dashed lines represent the 95% prediction interval of the equations.

maize yields and N_2O emissions in other global regions with similar climate (tropical and sub-tropical) and soils: Latin America (LAM; Brazil, Mexico, French Guyana), South-East Asia (SEA; China's Hunan and Jiangxi provinces, Indonesia, Philippines), and Australia (AUS). This yielded a total of 23 studies with 116 data points (Table 1).

For our calculations, we used seasonal maize yields (i.e., yield per one cropping period) and seasonal cumulative N_2O emissions (standardized over four months to include N_2O emissions due to field preparation and harvesting). Yield-scaled N_2O emissions were either taken directly from the published studies, or, if not reported, were calculated by dividing seasonal cumulative N_2O emissions by seasonal yields. To calculate yield gaps, we subtracted the maize yield for each study from the water-limited yield potentials (Y_w) of the nearest field station reported in the Global Yield-Gap Atlas project (www.yieldgap.org, see Supplementary Table 2 for a list of used stations) [7,44]. The water-limited yield potential is the yield of a crop cultivar when nutrients are non-limiting and biotic stress is controlled, but water supply is below crop demand. Crop growth is estimated based on solar radiation, temperature, atmospheric CO_2, plant breed, soil type and field topography [45,46]. The difference between observed yields and Y_w is the yield gap, which is given as percent of water-limited yield potential (%Y_w).

To establish a relationship between yield gaps (% Y_w) and seasonal N_2O emissions (cumulative and yield-scaled), we tested various regression functions and used the coefficient of determination (R^2), the corrected Akaike Information Criterion (AICc) and the Standard Error of Estimate to assess model fit. The best-fit function between cumulative N_2O and yield gaps (% Y_w) (Eq. (1), Figure 1e) was then used to project N_2O emissions to all of SSA when maize yield gaps are reduced by 50% and 70% (Figure 1c and d). For this, we used the yield gap maps for maize (Mg ha^{-1} season^{-1}) from Mueller *et al*. [5•], and converted them to relative yield gaps (% Y_w) using the local water-limited yield potentials reported in the same source [5•]. These local yield potentials were based on high-achieving yields reported at the political unit level; therefore, they are lower than high-achieving yields of individual farmers, field trials, or simulation models. Field trials are often conducted by trained personnel under supervision of agronomists, and much care is taken to ensure a good outcome of the trial. However, few smallholder farmers have access to this type of knowledge and resources. Therefore, for upscaling we decided to use the more conservative estimate of yield potentials by Mueller *et al.* [5•].

These spatially explicit relative yield gaps (Figure 1a) were then used to create the maps of projected N_2O emissions in Figure 1c and d using Eq. (1) (shown in Figure 1e) and reducing yield gaps by 50% and 75%. Spatial upscaling was conducted on 5 arc minute resolution (0.083×0.083 degrees) and the data were limited to SSA. Seasonal N_2O emissions were scaled to annual emissions using the number of cropping seasons per grid cell based on WorldCLIM climate layers [47,48]. Emission totals were calculated by scaling per-hectare emissions of individual grid cells with the appropriate surface area of the individual grid cells. All N_2O data are presented as kg N_2O-N year^{-1}. The projected annual N_2O emissions at 50% and 75% yield gap reduction were summarized by country (Supplementary Table 1) and geographic region according to the African Union (Table 2). We compared our projections to current N_2O emissions from agricultural soils for the year 2015 (Figure 1b), which were taken from the Emission Database for Global Atmospheric Research (EDGAR v5.0, layers IPCC 3C2 + 3C3 + 3C4 + 3C7) [49]. The reader should be aware that EDGAR data are not specific for maize but contain all crops.

Current situation

Cumulative seasonal N_2O emissions in the reviewed studies growing maize in SSA (Table 1) ranged from 0.05 to 3.53 kg N_2O-N ha^{-1}, with a mean ($\pm$1 SD) of 0.51 ± 0.07 kg N_2O-N ha^{-1}. The lowest N_2O emissions were measured in maize production on Oxisols in western Kenya fertilized with 50 kg N ha^{-1} of synthetic fertilizer [27], while the highest N_2O emissions were also reported from western Kenya, but on an acric Ferralsol growing maize using integrated soil fertility management (ISFM) [67], combining organic N sources, such as plant residues and farm-yard manure, with synthetic N amendments (total added N was 241 kg N ha^{-1}) (Rogers Rogito, personal communication). In comparison, cumulative seasonal soil N_2O emissions ranged from 0.13 to 4.16 kg N_2O-N ha^{-1} in LAM (mean 1.32 ± 0.32 kg N_2O-N ha^{-1}), and from 0.14 to 3.95 kg N_2O-N ha^{-1} in SEA (mean 0.94 ± 0.13 kg N_2O-N ha^{-1}). Seasonal maize yields ranged from 0.1 to 10.6 Mg ha^{-1} (mean 4.2 ± 0.3 Mg ha^{-1}) in SSA, from 2.3 to 14.6 Mg ha^{-1} (mean 7.1 ± 0.8 Mg ha^{-1}) in LAM, and from 0.1 to 12.0 Mg ha^{-1} (mean 3.9 ± 0.6 Mg ha^{-1}) in SEA. Yield-scaled N_2O emissions ranged from 0.01 to 3.63 kg N_2O-N Mg^{-1} in SSA (mean 0.26 ± 0.08 kg N_2O-N Mg^{-1}), from 0.07 to 0.43 kg N_2O-N Mg^{-1} in LAM (mean 0.19 ± 0.03 kg N_2O-N Mg^{-1}), and from 0.09 to 4.29 kg N_2O-N Mg^{-1} in SEA (mean 0.70 ± 0.18 kg N_2O-N Mg^{-1}).

Future N_2O emissions at 50% and 75% closed yield gaps

The relationship between relative yield gaps (YG, expressed as % of local yield potential) and cumulative soil N_2O emissions was best described by an exponential decay function, with similar relationships for measurements from SSA, LAM, SEA and AUS. Therefore, we used a model based on the combined data from SSA + LAM + SEA + AUS (Figure 1e, Eq. (1), $R^2 = 0.48$, Standard Error of Estimate = 0.615) to project future soil N_2O emissions under the 50% and 75% yield-gap closure scenarios (Figure 1c + d).

$$\begin{aligned} &Cumulative\, N_2O\, emissions\, \left(\text{kg N ha}^{-1}\,\text{season}^{-1}\right) \\ &\quad = 0.105 + 2.369 * e^{-0.029 * YG(\%)} \end{aligned} \tag{1}$$

This model shows that closing yield gaps by 50% will likely triple area-based N_2O emissions from current 'baseline' N_2O emissions of 0.24 to 0.66 ± 0.18 kg N_2O-N ha^{-1}. Further reducing yield gaps by 75% will increase

Table 2

Mean area-based N_2O emissions (kg N ha^{-1} year^{-1}) and total emissions (Gg N year^{-1}) for current conditions, and after closing yield gaps (YG) by 50% and 75% due to increased N input from fertilization, for sub-Saharan Africa

African Region[a]	Area (km^2)	N_2O emissions (kg N ha^{-1} year^{-1})[c]						Total N_2O emissions (Gg N year^{-1})[d]		
		Current[b]		YG closed 50%		YG closed 75%		Current[b]	YG closed 50%	YG closed 75%
Central	1,938,942	0.12	±0.14	1.01	±0.18	1.62	±0.16	14	187 ± 34	302 ± 40
Eastern	3,240,761	0.43	±0.26	1.15	±0.24	1.77	±0.31	137	352 ± 58	542 ± 68
Southern	3,451,230	0.18	±0.14	0.90	±0.12	1.48	±0.10	39	320 ± 59	522 ± 70
Western	2,331,130	0.29	±0.17	1.09	±0.14	1.66	±0.13	65	253 ± 42	388 ± 49
Total SSA	10,962,063	0.27	±0.21	1.05	±0.19	1.64	±0.21	255	1112 ± 193	1755 ± 226

[a] According to the African Union Geoscheme.
[b] Current emissions are from EDGAR v5.0 (agricultural soils) for the year 2015 [49].
[c] Data are means ± CI.
[d] Shown are sums ± CI of area-based emissions multiplied with the total area.

area-based N_2O emissions by a factor of five to 1.25 ± 0.21 kg N_2O-N ha^{-1}. For comparison, Huddell *et al.* [68] estimated that a tripling of N fertilizer use from 50 to 150 kg N ha^{-1} would increase cropland N_2O emissions in the tropics by 30% to 0.82–1.07 kg N ha^{-1}, but they noted a large variation of N emissions across sites receiving similar N inputs, originating from differences in soil type, precipitation and agricultural management.

Highest increases in N_2O emissions will occur if the final 25% of the yield gap are closed, with area-based N_2O emissions rising to a mean of 2.5 ± 0.4 kg N ha^{-1}, which is a more than a 10-fold increase compared to current emissions. This exponential increase of soil N_2O emissions at the end of the curve most likely occurs because attaining the full water-limited yield potential of maize requires N fertilization rates >100 kg N ha^{-1}, which can lead to excess soil N availability beyond plant N demand, especially if fertilization and plant N uptake are not synchronized [26••,28••,27].

The relationship between yield gaps and yield-scaled N_2O emissions followed an exponential growth curve (Figure 1f, Eq. (2), $R^2 = 0.85$, Standard Error of Estimate = 0.296):

$$\begin{aligned} &Yield-scaled\,N_2O\,emissions\left(\text{kg N Mg}^{-1}\text{ yield}\right) \\ &\quad = 0.140 + 6.80{*}10^{-13}{*}e^{0.295{*}YG(\%)} \end{aligned} \tag{2}$$

Yield-scaled emissions were highest at the highest yield gaps (i.e., at yields <1 Mg ha^{-1}). Consequently, reducing yield gaps by 25% resulted in large reductions in yield-scaled N_2O emissions (from 4.55 to 0.14 kg N_2O-N Mg^{-1}), whereas further closing of the yield gap did not change yield-scaled emissions, not even when yield gaps were completely closed. This means that if yield-scaled N_2O emissions from maize fields are to be reduced, the largest gains can be realized at the farms with lowest maize production.

When comparing our projections to the current N_2O emission estimates for agricultural soils from the EDGAR database for 2015 (which uses a Tier 1 approach following IPCC guidelines), closing yield gaps by 50% will more than quadruple cropland N_2O emissions in SSA, from 255 to 1112 ± 193 Gg N $year^{-1}$ (+337%, Table 2). Hickman *et al.* [69] estimated that total agricultural N_2O emissions (including direct emissions from soils, as well as N_2O emissions from manure management and pasture) from SSA would roughly double until 2050 (from 622 to ca. 1200 Gg N $year^{-1}$) due to agricultural intensification (assuming a 1.5–6 fold increase in N input to agricultural fields). According to our projections, large relative increases will be observed in Central SSA, from 14 to 187 ± 34 Gg N $year^{-1}$ (+1245%), with hotspots in Cameroon, Republic of the Congo and Democratic Republic of the Congo (Figure 1c), and in Southern SSA (+712%, from 39 to 320 ± 59 Gg N $year^{-1}$), with hotspots in South Africa, Angola, Zimbabwe and Zambia. The relative increase in N_2O emissions is intermediary in Western SSA (+290%, from 65 to 253 ± 42 Gg N $year^{-1}$), with hotspots in Côte d'Ivoire, Ghana and Burkina Faso, while the lowest relative increase in N_2O emissions will be observed in Eastern SSA with an increase from 137 to 352 ± 58 Gg N $year^{-1}$ (+158%), and hotspots being located in Uganda, Kenya, Ethiopia and Tanzania. This variation between African regions might be related to different fertilizer application rates across the different regions [6], resulting in different values for the current yield gaps as well as differences in current N_2O emissions. For example, while cropland N_2O emissions from Central and Southern Africa are low (<0.25 kg N ha^{-1} $year^{-1}$), N_2O emissions from croplands in some areas of Eastern Africa (esp. Lake Victoria region in Kenya, Uganda, and Rwanda, as well as the Ethiopian highlands) and Nigeria are considerably higher (ranging from 0.75 up to 2 kg N ha^{-1} $year^{-1}$). Therefore, because Eastern and Western Africa start from a higher N_2O emission level, relative N_2O emission increases due to cropland intensification are lower compared to regions that have low N_2O emissions. Other reasons for the variation in N_2O emissions could be related to spatial and temporal variability of water availability and long-term N application rates [70].

Closing yield gaps by 75% will further increase total N_2O emissions from SSA to 1755 ± 226 Gg N $year^{-1}$, representing an almost sevenfold increase (+589%) from current cropland N_2O emission levels reported in the EDGAR database (Table 2, Figure 1d), and a 47% increase of total anthropogenic N_2O emissions from SSA (currently 1190 Gg N $year^{-1}$ [71]). The reader should keep in mind that our projected N_2O emission increase only considers direct N_2O emissions from fertilized soils, but it does not include indirect emissions downstream or downwind due to leaching or volatilization of fertilizer-N and is, therefore, conservative. In addition, increasing N fertilizer application to close yield gaps might lead to the release of other N compounds that are detrimental to environmental, human and animal health, such as ground water pollution via nitrate leaching [68], and volatilization of NH_3 and NO_x [72–74]. Projecting how closing yield gaps would affect the release of these compounds is beyond the scope of this review; however, future studies should consider these and examine the potential co-benefits or trade-offs of agricultural management decisions.

Our N_2O emission projections are based on an increase in area-based N_2O emissions and assume that the current cropland area remains constant. Mean area-based N_2O emissions across the different regions of SSA will increase from currently 0.27 ± 0.21 kg N ha^{-1} $year^{-1}$ to

1.05 ± 0.19 kg N ha^{-1} year^{-1} if yield gaps are closed by 50%, and up to 1.64 ± 0.21 kg N ha^{-1} year^{-1} if yield gaps are closed by 75% (Table 2). However, it should be noted that most studies measured N_2O emissions over a limited period of increased N inputs (fertilizer trials) and often in low-fertility soils. Over time and with better soil management, SOM content and fertility should increase, which could further increase area-based N_2O emission rates. Furthermore, the studies available for SSA were only examining N_2O emission increases caused by increased N fertilization rates. Whether, and by how much, N_2O emissions will change if the share of irrigated cropland increases, or if climate change exacerbates water scarcity, cannot be answered here given the lack of studies testing the effect of irrigation and water availability on soil N_2O emissions in SSA.

Model uncertainty

We acknowledge that the comparison of our N_2O emission projections with the EDGAR database has limitations: first, EDGAR does not provide N_2O emissions specific for maize but summarized for all crops. To our knowledge, spatially explicit estimates of soil N_2O emissions for only maize do not exist for SSA. Second, the EDGAR database is based on N fertilizer use maps, which contain large uncertainties for some African nations, especially regarding organic N use (e.g., animal manure, plant residues, and N derived from biological N_2 fixation by legumes) that is difficult to quantify. Third, EDGAR relies on N_2O emission factors (EFs, i.e., 1% of fertilizer-N emitted as N_2O-N) because most of the countries in SSA do not have the required data to report on a Tier 2 or Tier 3 basis. However, several studies have reported a poor fit of the default N_2O-EFs to the situation in SSA [29], possibly due to non-responsive and depleted soils [27,75], or due to the use of organic fertilizer that provides a large source of labile C in addition to the N that could promote denitrification [76]. Fourth, the studies reporting soil N_2O emissions presented here all originate from Eastern and Southern SSA, which constitutes a certain bias since conditions in Western and Central SSA might be different (e.g., soil types, climate, elevation, management techniques, maize genotypes). Nevertheless, measurements in SSA showed similar results compared to other tropical and subtropical regions of LAM, SEA and AUS, which makes us confident that our projections provide valuable insight into future patterns of soil N_2O emissions when maize yield gaps are being closed.

Conclusions

To ensure food security of the growing populations in SSA, grain yields need to increase. Closing the yield gap for maize by 75% through increased N fertilizer application rates ($>80-100$ kg N ha^{-1}) is expected to triple current maize yields in SSA (from 1.2 to 3.5 Mg ha^{-1} season^{-1}, [5•]) while also increasing soil N_2O emissions by almost sevenfold. It should be noted, however, that maize yields in SSA may also be limited by water availability or availability of other nutrients such as P that were not considered in our calculation. This sevenfold increase in N_2O emissions though, may be acceptable as the fertilizer application should result in increased soil fertility and thus a smaller yield gap. This yield-gap reduction would also alleviate land pressure, thus limiting or even avoiding expansion of agricultural land into natural land. Thus, increased fertilization should be put into context with GHG emissions that can be (i) avoided (e.g., by preventing soil degradation and SOM mineralization) or (ii) offset via C sequestration due to better soil management (e.g., via buildup of additional SOM due to increased residue input), and (iii) with emissions that would otherwise occur elsewhere due to cropland expansion (e.g., via deforestation and grassland conversion). Future studies, therefore, could investigate linking ecosystem responses to yield gaps, for example to assess the consequences of productivity on cropland soil C stocks. Finally, this regression between cropland N_2O emissions and yield gaps provides an improved understanding of the environmental consequences of poor agricultural practices that is essential to inform climate-smart practices, as long as consideration is given to the sustainability of the wider production environment.

Conflict of interest statement

Nothing declared.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.cosust.2020.08.018.

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